IEA/H2/T11/FR1-2000

INTERNATIONAL ENERGY AGENCY
HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Chapter 1 of 11

T. Schucan
Paul Scherrer Institute
Switzerland

Chapter 1
SOLAR-WASSERSTOFF-BAYERN HYDROGEN DEMONSTRATION PROJECT AT NEUNBURG VORM WALD, GERMANY

1. PROJECT GOALS

The overriding aim of the Solar-Wasserstoff-Bayern (SWB) hydrogen project is to test, on an industrial demonstration scale, major technologies of the hydrogen cycle utilizing electric power generated without releasing carbon dioxide (in this instance, photovoltaic solar energy). Different technologies were compared and tested in interaction with other plant subsystems. Suppliers of the equipment were invited to collaborate in developing the test programs, with the intention of promoting interest on the part of industry and stimulating research and development efforts, since there is practically no market as yet for hydrogen systems concerned. Foremost among the aims of SWB and its shareholders is the acquisition of know-how for planning, realizing and operating (solar) hydrogen plants, sustained by evolving knowledge of internal system structures and actions (as distinct from pure black box operation). Another objective is to engage in realistic public relations work supported by first-hand information. This project will be terminated at the end of 1999, after successfully meeting the program goals.

2. GENERAL DESCRIPTION OF PROJECT

Major system components were installed on an industrial scale at a demonstration facility located in Neunburg vorm Wald, Germany for a potential future energy supply based on hydrogen generated by utilizing (solar) energy unaccompanied by release of carbon dioxide. Initial technical aspects of the stepwise transition from our present-day energy supply primarily aligned for fossil fuels were considered. Most of the plant subsystems are prototypes of innovative technologies. Among others, the facility includes photovoltaic solar generators, water electrolyzers, catalytic and advanced conventional heating boilers, a catalytically heated absorption-type refrigeration unit, fuel cell plants for stationary and mobile application, an automated liquid hydrogen (LH_2) filling station for test vehicles, and a gaseous hydrogen (GH_2) filling station.

Focal points of the investigations were performance of the plant subsystems and their interaction under practical operating conditions. Analysis of the work yielded a reliable database for updated assessment of the prospects and challenges of solar hydrogen technology.

Founded at the end of 1986, SWB is a joint venture with 70% of the shares held by Bayernwerk AG and 10% each by BMW AG, Linde AG (both through wholly owned subsidiaries) and Siemens AG. One of the original cofounders, Dasa, withdrew in 1994. The capital invested in the SWB project over the full run of 13 years is approximately DM 59 million (US$33 million, at an exchange rate of 1.80 DM/US$) in public funds, and DM 69 million (US$38 million) from SWB shareholders.

SWB has operated the aforementioned demonstration facility to develop an understanding of a possible future solar hydrogen energy supply scheme. The project was organized in two phases. Phase 1 was completed at the end of 1991, and Phase 2 is to be completed at the end of 1999.

3. DESCRIPTION OF COMPONENTS

An impression of the size and layout of the overall facility may be obtained from Picture 1.1. The aerial photograph shows the operating and multi-purpose building and the plant subsystems installed outdoors, including the south-oriented photovoltaic solar fields, $H_2/O_2/N_2$ storage vessels and the liquid hydrogen filling station. The main systems of the overall facility are mapped out in the block flow diagram of Figure 1.1 and discussed in the following subsections.

Picture 1.1: Aerial view of SWB solar hydrogen facility

3.1 Plant subsystems for hydrogen production and storage

- Nine fields of solar generators employing monocrystalline, polycrystalline and amorphous silicon technology with a total rated field capacity of 370 kW_p and efficiencies of 9-13% (crystalline) and 5% (amorphous) measured at standard test conditions, based on module surface area, and includes cable losses.

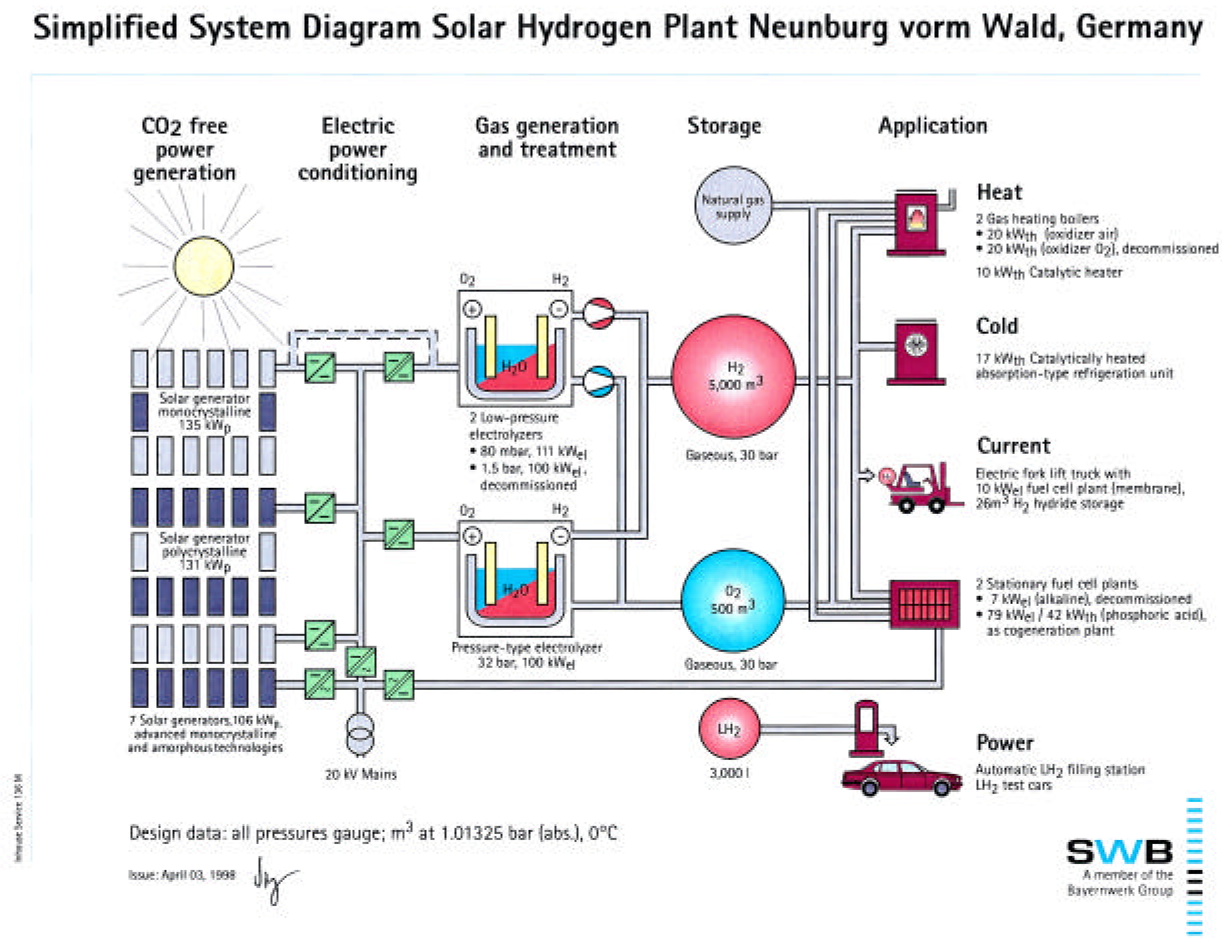


Figure 1.1: Simplified block diagram of SWB solar hydrogen facility

- Electric power conditioning units (DC-DC converters, DC busbar, electrolysis power supplies, converters, AC busbar, DC-AC converters).
- Two advanced low-pressure water electrolyzers employing different technologies, rated at 111 kW_{el} and 100 kW_{el} capacity, with a total maximum hydrogen output of 47 Nm^3/h.
- Alkaline pressure-type electrolyzer, 100 kW_{el}, working pressure 32 bar.

Hydrogen and oxygen gas systems for compression, purification, drying and storage of the electrolytically generated gases (purity 99.9 vol% H_2 and O_2 or better).

3.2 Plant subsystems for hydrogen utilization

- Two gas-fired heating boilers of calorific-value design working with different oxidizers (oxygen and air), capacity of each is 20 kW_{th}, burning natural gas/hydrogen fuel mixture percentages between 5-95 vol%, as well as natural gas alone.

- Catalytic heater of calorific-value design (10 kW_{th} boiler output) fueled with natural gas and mixtures of natural gas/hydrogen (90/10 vol% to 50/50 vol%) with air as oxidizer. This heater is integrated into the on-site building heating system.
- Catalytically heated absorption-type refrigeration unit (rated burner output 32.6 kW_{th}, rated refrigeration capacity 16.6 kW_{th}) with hydrogen as the fuel and air as the oxidizer. This unit supports the conventional chilled water circuit.
- Two fuel cell plants employing different technologies, alkaline type of 6.5 kW_{el}, phosphoric acid type of 79.3 kW_{el} and 42.2 kW_{th} (hydrogen fuel) or 13.3 kW_{th} (natural gas fuel) output.
- Fuel cell plant with proton-exchange membrane operating with air as the oxidizer, rated power output 10 kW_{el}, for mobile application in an electric forklift truck with hydrogen supply from metal hydride storage.
- Automated LH_2 filling station for testing automobile fueling systems, including comparison of two clean-break coupling systems of new design, operation of a cryogenic pump system, and testing of a vehicle fuel tank system without cryovalves.

4. INTEGRATION OF COMPONENTS

In describing integrated hydrogen systems, the emphasis is most often placed on the major components (PV panels, wind turbines, electrolyzers, compressors, fuel cells, etc). In fact, there are a number of essential subsystems, referred to as peripherals or balance-of-plant, that are vital to plant operation. These include utility and auxiliary subsystems (instrument/operating air supplies, nitrogen supply, demineralized water/KOH systems, ventilation, e.g.), process and safety control subsystems, and extensive test data acquisition subsystems. In addition, power conditioning (converters and inverters) play an important role in the operability and efficiency of the overall system. These subsystems are often overlooked in the process design and costing phases of projects. Cost overruns and operational delays can be avoided or reduced by paying proper attention to these important subsystems.

At SWB, particular attention was paid to the integration of the components and to the operability of the facility as an integrated plant, resulting in a well-integrated operating facility. Some of the coupling issues investigated in detail were:

- The electricity produced by the photovoltaic fields was distributed and/or transformed according to downstream needs. Surplus PV electricity was supplied to the grid, while electricity supply from the grid was used in other cases. Direct coupling of solar generators and electrolyzers was also possible.
- Generation, treatment and storage (G/T/S) of hydrogen and oxygen were adjusted to the downstream needs.
- Each of the various end use applications possible in the SWB facilities (i.e., production of heat, cold, or mechanical power) requires its own mixture of hydrogen, natural gas and oxygen and its own combination of G/T/S subsystems.

SWB did not select any optimum integrated system, but tested all possible varieties and many desirable combinations of applications, including different choices of solar generators or electrolyzers.

The process control system was supplied by the Power Generation Group (KWU) of Siemens AG. It consisted of a local control level by a programmable logic controller (PLC) for each subsystem, an open bus-system (Sinec-H1-Highspeed bus, Sinec-L2-Fibre Optical field bus) and a central control and monitoring system (5 computers PC-Pro M5 with operating system REAL 32). Some of its major characteristics are high availability by self-diagnostic, high transmission-safety via message protection, redundant archiving of data, and automatic reprints to guarantee updated documentation.

5. PERFORMANCE AND OPERATIONAL EXPERIENCE

Only a very compressed summary of the wealth of results obtained in test operation to date can be given here. In reviewing these it may be noted that the cumulative operating times logged for the various plant subsystems differ considerably according to the test programs run (i.e., alkaline low-pressure electrolyzer 6000 h, membrane electrolyzer 2000 h, catalytic heater 5200 h, PAFC fuel cell plant 3900 h, LH_2 filling station 900 h).

The first systems in operation were the solar generators at the beginning of 1990. The larger solar generators feed power through maximum power point (MPP)-controlled DC-DC converters to a common DC busbar interconnecting the solar generators, electrolyzers and AC power grid.

In the interests of better investigating the interaction of major plant subsystems, more flexible and accordingly more extensive electric power conditioning was provided than would have been necessary for operation exclusively in parallel with the AC power grid via DC-AC converters. Current feed to the electrolyzers is controlled by electrically isolating electrolysis power supply units. Direct or simulated direct coupling of the electrolyzers to a solar generator can also be made by appropriate electrical connection.

5.1 Solar generators and converters

The solar generators and associated converters installed during Phase 1 (the two major fields with 130 kW_p each) have been in operation for over seven years. Among the problems encountered in the photovoltaics to date were initially undetected damage incurred during installation and premature ageing of surge arresters. Both led to deterioration of insulation, resulting in the need for replacement of some modules and surge arresters. Changes were necessary in the method of measuring insulation level.

The monocrystalline field is operating well, but internal electrical defects have been found in a growing number of polycrystalline modules (30% thus far). This manifests itself in interruption of the series connectors of the cells. Experience with these faults has since led the manufacturer to introduce production improvements.

The defective modules have been dismantled. The number of modules sustaining glass breakage due to tension dating from the time of installation has stabilized. For a time, frequent failure of control cards was observed on the converters due to premature ageing, presumably caused by thermal stress. Energy harvest of the main solar fields is good, verifiably better than the figures reported by some other system operators in Central Europe.

In the winter of 1993/94, six new solar generators were installed. The efficiency of some crystalline technologies fell distinctly short of guarantee figures. In some cases, the necessary repairs or replacements undertaken by the suppliers proved successful. Efficiency of the two fields using amorphous technology met the guarantee levels. The degradation observed to date of 8-10%, depending on the technology, is in line with expectations.

Operation of most of the Phase 2 DC-DC and DC-AC converters also was not immediately satisfactory, which is only partly to be explained by the prototype nature of these units. Subsequent improvements, some of appreciable magnitude, were proved to be necessary.

5.2 Electrolyzers

5.2.1 Low pressure electrolyzers

The two low-pressure electrolyzers, installed in Phase 1, are advanced technology systems (zero gap geometry, absence of asbestos diaphragms, activated electrodes, increased current density) and exhibit significantly lower specific energy consumption than conventional designs (4.5 kWh/m^3 H_2 at rated current).

Problems occurring with the alkaline electrolyzer, notably inadequate purity of the product gases, were eliminated in August 1992 by installing polysulphone diaphragms reinforced on the cathode side to replace the previous plain type. Test results gathered over several years indicate that the alkaline low-pressure electrolyzer is working well. Test programs have largely been completed. Further work with this equipment will primarily add to experience with long-term operation. Cyclic recording of basic values (characteristics) is being made.

The membrane electrolyzer had to be shut down in June 1995 because of increasingly deficient product gas purities (above all, H_2 in product O_2). Up to the time it was decommissioned, the membrane unit also worked well even under conditions of greatly varying power input when directly coupled to a solar generator.

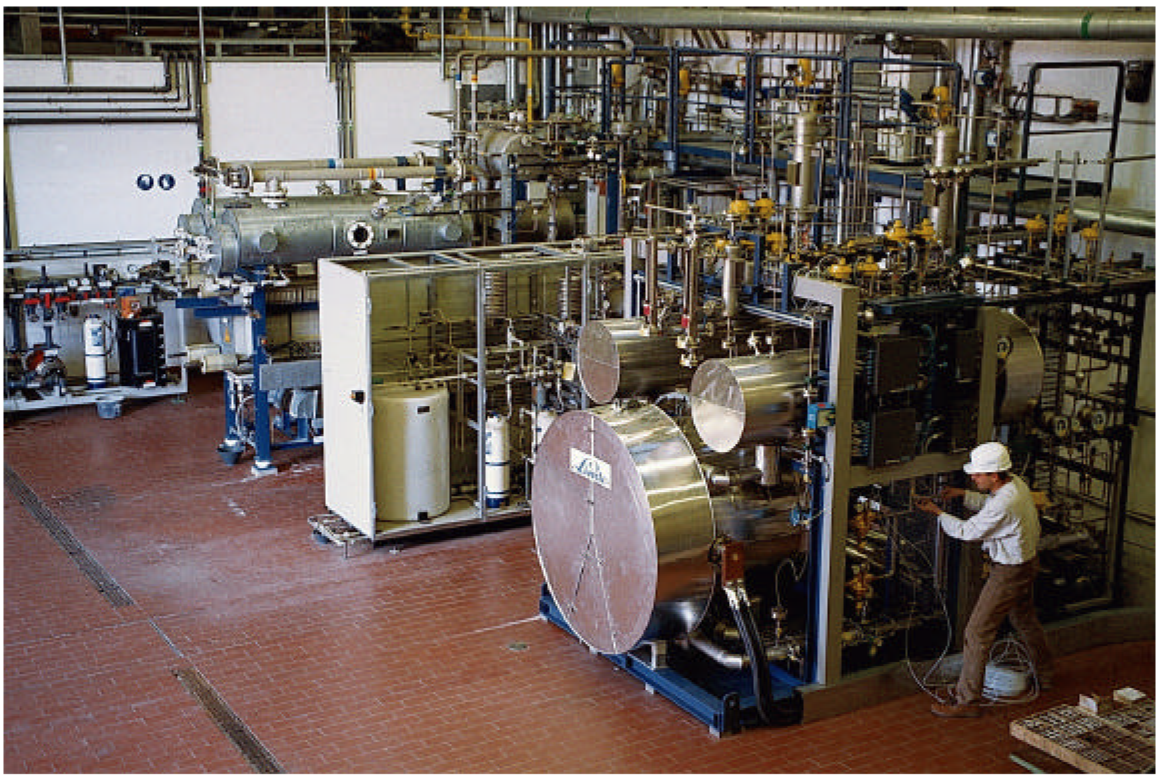
SWB's acquired know-how was available to the manufacturers for use in further development, but both have since abandoned this field of activity. Procurement of spare parts has become very difficult as a result, particularly affecting the membrane electrolyzer. After dismantling the cell stack in February 1996, the membranes were found to have deteriorated severely during the five years of test operation. The electrolyzer performed well over a long period, but had to be decommissioned owing to the lack of spare parts.

5.2.2 Pressurized electrolyzer

Advanced pressurized electrolyzers of the 100 kW_{el} class working at about 30 bar were not available at the time the two low-pressure units were purchased. Placement of an order for an alkaline electrolyzer (with unitized EDE ceramic diaphragms and nickel electrodes) was delayed until November 1994. The guarantee test run for the unit took place in July 1996. Operating at 135°C, the specific energy consumption was about the same as for both low-pressure units, but no compression of the product gases was required in this case. The main characteristics of this unit are 30 bar pressure, operation with intermittent power sources, and quick response on load changes.

The first recording of basic data was interrupted at the end of 1996 when dismantling of the EDE cell stack became necessary, primarily due to rising O_2 impurity in the product H_2. Under the terms of guarantee, it was agreed that the supplier would install a cell stack of different makeup (polysulphone diaphragms with ceramics, chemically activated nickel electrodes, working temperature reduced to 105°C, new gasket design). A demister was inserted in the O_2 separator to reduce the KOH content of the O_2 product gas. SWB agreed to a one-year demonstration of this cell stack. However, although the specified characteristic values have been attained, a test run could not be performed due to a number of problems. After removing the demister and installing a third version of a cell stack (polysulphone diaphragms with ceramics, non-activated nickel electrodes) the test program resumed in May 1998. The electrolyzer was operating in more or less stable conditions until it had to be shut down again in August 1998 due to deficiencies in the cell voltage measuring lines.

With this third configuration of cell stack, at an operating temperature of 105°C, the specific energy consumption is 4.7 kWh/m^3 H_2, and the current density is 8.4 kA/m^2, at rated load. The three electrolyzers are shown in Picture 1.2.



Picture 1.2: Three electrolyzers (pressurized electrolyzer is right front)

5.2.3 Hydrogen and oxygen gas systems

Pressure storage of H_2 and O_2 generated by the two low-pressure electrolyzers requires subsequent compression of the product gases. Both gases are then cleaned of impurities (the other gas component) by catalytic combustion, dried in regenerated beds of alumina gel/molecular sieves, and finally stored in pressure vessels.

After correcting a number of defects (decentralized process control system, compressors, valve leaks caused by entrained particles of adsorbent, analyzer gas coolers), the H_2/O_2 gas systems are working satisfactorily. Occasional problems (including increased piston ring and cylinder wear) are still experienced with the hydrogen compressors, however, probably due in part to the test operation philosophy as practiced at Neunburg vorm Wald.

In addition to pressure storage of gas, liquid hydrogen (from an outside supplier) is stored in the liquid state for road transport utilization.

A special feature is the capability of operating some plant subsystems (gas-fired heating boiler, phosphoric acid fuel cell plant and catalytic heater) on either natural gas or hydrogen as well as partly on mixtures of natural gas and hydrogen.

In this way it is possible to demonstrate and investigate, at least at a preliminary level, the technical aspects of stepwise transition from contemporary energy supply based mainly on fossil fuels to a possible scenario where the energy medium employed is hydrogen generated without concomitant production of CO_2.

5.2.4 Heating boilers and refrigeration units

Although delivering reasonable test results in the past, the gas-fired heating boiler operating with oxygen as the fuel oxidizer was unable to reach an acceptable level of availability owing to problems (insufficient stability of the burner head) and the unit was decommissioned in May 1995. By contrast, the heating boiler operating with air as the oxidizer continues to work satisfactorily.

As expected, the efficiency was better when using oxygen instead of air with other conditions unchanged. Combustion of hydrogen with air resulted in slightly increased emissions of NO_x compared to combustion of natural gas. Significantly increasing the amount of excess air results in reduction of these emissions, but at the expense of efficiency.

Test programs for the gas-fired heating boiler with air as the fuel oxidizer have largely been completed. Further work with this equipment will primarily add to the experience of long-term operation. Cyclic recording of basic values (characteristics) is being made.

The calorific-value catalytic heater with a boiler capacity of 10 kW_{th}, designed to burn 100% natural gas or natural gas with a continuously variable mixture of 10-50 vol% H_2 was handled as a development project. Air was used as the fuel oxidizer, with external premixing of fuel gas and air. Owing to the reduction of combustion temperature below 900°C, NO_x emissions are less than 20 mg/kWh. Test operation of this unit started in December 1995.

Another development contract was placed for the catalytically heated absorption-type refrigeration unit fueled with hydrogen. A conventional absorption-type refrigeration unit for air conditioning service, fired with natural gas, was modified for this application.

Running air as the fuel oxidizer in the unit generates a refrigeration capacity of 16.6 kW_{th}. Heat is produced catalytically on diffusion burner structures (without premixing of fuel and oxidizer, which in principle eliminates backfiring). Due to the low burner working temperature of approximately 800°C, heat transfer in the high-pressure desorber is very efficient. Moreover, the possibility of corrosion problems is reduced by the coolant not being subject to overheating (≤160°C) in the desorber. NO_x emissions are less than one ppmv.

Several improvements had to be made to the refrigeration unit in the beginning, due to a number of problems with standard components; for example, the burner monitor and off-gas sampling piping. The unit is used to support the conventional chilled water circuit.

5.2.5 Stationary fuel cell plants

By the end of 1997, two fuel cell plants (alkaline and phosphoric acid) were tested by SWB. These two types are designed for different spheres of use.

Because it requires pure O_2 as the oxidizer and pure H_2 as the fuel, the alkaline fuel cell is more suitable for special niche applications (i.e., in space vehicles and submarines). These operate in conjunction with a so-called hybrid system – comprised of a DC-DC converter, battery buffer, converter and control unit. The alkaline fuel cell plant at SWB allowed reproducible simulation of electric vehicle running cycles under stationary conditions.

Following reversal of electrical polarity in individual cells, additional measures were adopted in the supply systems and monitoring of the feed gases. Several replacements of the fuel cell stack became necessary, leading to the decision in October 1994 to decommission this plant even though it had demonstrated good performance during periods of trouble-free operation. Electrical efficiency is related to gross calorific value and disregarding electrical utility consumption, and was measured at 53% at rated load. Current density was 4 kA/m^2 and random load transients were obtained within about 100 ms.

Experience with the alkaline fuel cell plant proved it to be too sensitive, due to its complexity. Above all, its usability is compromised by the risk of irreversible damage to the nickel anode. The manufacturer relinquished this field of activity some time ago in favor of the proton-exchange membrane fuel cell technology.

The phosphoric acid fuel cell plant (incorporating the possibility of heat decoupling) is regarded as an alternative to conventional heat-and-power cogeneration plants. The combination of hydrogen generation by steam reforming of natural gas including CO shift conversion and fuel cell technology is meaningful in view of pipeline supply of hydrogen not being available in quantities to meet energy supply requirements in the near future. By reason of the good overall efficiency of this type of fuel cell plant, CO_2 emissions are lower than with conventional systems.

Testing of the previously mentioned transition scenario can be made at Neunburg vorm Wald by operating the phosphoric acid fuel cell plant (Pictures 1.3 and 1.4) either with natural gas from the public network or with hydrogen supplied direct from on-site gas storage. Ambient air is used as the oxidizer. To increase the fuel cell stack efficiency by up to 3 percentage points, the air may alternatively be enriched with oxygen to a maximum of 50 vol% O_2

Optimized for electric power output, the phosphoric acid fuel cell plant is designed to run in a variety of modes for test operation in a (solar) hydrogen demonstration facility. Heat is decoupled at 165°C and the operating temperature is 190°C. In other words, it is not designed as a commercial containerized standard unit.

Major problems occurred at the time of commissioning this plant, necessitating extensive repairs and changes, as well as considerable expense of time and labor for optimization in view of the high level of automation. The resulting delays caused substantial postponement of the guarantee test run. Most of the difficulties originated in the associate peripheral systems, with very few in the fuel cell stack itself.

The test program has proceeded at a good pace since March 1993. The first tests conducted in various modes for recording characteristics were run at the end of 1993. Load following and continuous operation (24 hours a day, 5 days a week) were investigated in 1994. In the summer of 1995 the plant was used in a simulation of the power requirements of a small hospital in an island-site operation.

Picture 1.3: PSA Unit **Picture 1.4: Phosphoric acid fuel cell plant**

The starting and stopping behavior of the fuel cell plant was investigated more closely in the autumn of 1996 and measurements were made to check emission levels (CO and NO_x). Emissions are comparable with other commercially available phosphoric acid fuel cell plants, meaning that they are several orders of magnitude lower than the levels specified for gas engines (German TA Luft specifications).

Apart from these test periods, the phosphoric acid fuel cell plant was operated mainly at rated capacity (fuel cell at 610 A_{DC}). Output and load change response conformed to expectations. Note may be made of the electrical utility power consumption, which was unexpectedly high at the time (12 kW_{el} with hydrogen, 32 kW_{el} with natural gas), and the higher heat generation when using natural gas (20 kW_{th} instead of anticipated 13 kW_{th}).

Within the test runs, special attention was given to the behavior of the fuel cell plant under conditions of intermittent operation as practised at SWB and as would be expected in a (solar) hydrogen energy supply scheme.

Valuable knowledge related to long-term stability was acquired, under highly aggravated operating conditions. The approximately 450 starts and stops to date over a cumulative total of about 2600 h of test operation have thus far resulted in output of the fuel cell decreasing by about 20 kW_{el}.

In December 1997, excessive H_2 concentrations occurred in the scavenging air of the fuel cell. The attempt to decrease the leakage caused by ageing of the seals by adjusting the tension in the cell stack, was unsuccessful. Remedy could be found by significantly increasing the scavenging airflow using the excess power of the cathode air compressor.

Test programs for the phosphoric acid fuel cell plant have largely been completed. Further work with this equipment will primarily add to experience of long-term operation. In addition to cyclic recording of basic values and characteristics, the main item of interest is further degradation of output.

5.2.6 Mobile fuel cell plant

The fuel cell plant with a proton exchange membrane, now on a trial run, was modified by the manufacturer for use of air (instead of oxygen) as the fuel oxidizer, which represents a new technology. It was constructed as a mobile system with a rated power output of 10 kW_{el} (operating temperature of 60°C, rated voltage of 52 V_{DC}), and serves as an electro-chemical power source to drive a standard electric forklift truck at the Neunburg vorm Wald site. The skid-mounted fuel cell plant was installed in the truck in place of the normal battery pack. Power for all electrical auxiliaries is supplied by the on-board system, using an external battery for start-up. In addition to its role as carrier of an experimental fuel cell demonstration plant for mobile and stationary tests of German PEM-technology, the forklift truck is also used for actual work, as shown in Picture 1.5. The fuel cell plant is shown in Picture 1.6.

Picture 1.5: Electric forklift truck at work

Picture 1.6: PEM fuel cell plant

The supplier was unable to meet the December 1996 acceptance date agreed at the time of ordering. Delay was caused by unforeseeable demands on the part of the licensing authorities. Among other things, provision of redundant system control and revision of the safety logic circuits were specified. The successful guarantee run was finally performed in December 1997. The agreed guarantees for effective electric power output of the fuel cell plant (≥9 kW net of electrical utility consumption), electrical efficiency of the fuel cell referred to net calorific value of hydrogen (≥50%), and total fuel cell plant efficiency (≥40%) were attained.

After overcoming initial deficiencies (problems with test data acquisition, unsuitable reaction water level indicators**,** defective pump motor for cooling water) during the trial runs starting in January 1998, the actual test operation proceeded satisfactorily, thus confirming the suitability of a membrane fuel cell plant in mobile operation. Due to the replacement of the normal battery pack for the membrane fuel cell plant, the weight conditions of the truck changed. Therefore, in July 1998, specific tests became necessary at the forklift truck maker to ensure safe operation again.

Metal hydride will be used for on-board hydrogen storage, which is advantageous in this special instance because of its weight. The effective hydrogen capacity is designed for 8 hours of forklift truck operation at average power requirement. The envisaged time for charging the hydride is about 10 min and the heat generated during the charging will be dissipated by an external cooling water circuit. This system gives SWB the opportunity to undertake practical testing and acquire corresponding experience with a third major hydrogen storage technology, complementing the pressurized gas and liquid hydrogen technologies already in use. The metal hydride is to be charged with hydrogen from onsite gas storage at pressures between 10 and 30 bar.

The entrance to the operating building on the west side has been converted as an access route for the electric forklift truck. The necessary hydrogen gas filling station is located in the operating building.

Conversions to the existing hybrid system (used in conjunction with testing of the alkaline fuel cell plant) have been completed, enabling its use for stationary testing of the membrane fuel cell plant to simulate vehicle drive cycles. As it now stands, the system can also be employed to verify any performance of the membrane fuel cell plant up to rated capacity. The air-oxidiser membrane fuel cell technology is well-suited for electric vehicles, in effect converting these to hydrogen gas fueling.

As an energy medium, hydrogen is environmentally friendly to a high degree on account of its chemical properties and thus is well-suited for use as a motor fuel, powering vehicles without locally producing noxious emissions.

5.2.7 Liquid hydrogen filling station

Work has been proceeding also on optimizing the liquid hydrogen fueling of test cars at Neunburg vorm Wald since 1991 with construction of a LH_2 filling station (Picture 1.7).

Through the pressure prevailing in the 3,000-liter site tank, liquid hydrogen is conditioned according to the vapor pressure curve and can be filled into the vehicle fuel tank either by the site tank pressure or by a LH_2 pump. The filling line is manually coupled to the vehicle whereas the actual filling operation takes place under program control.

Test results acquired to date by SWB have been evaluated to optimize the LH_2 filling station insofar as the time for a complete vehicle tank filling cycle has been shortened to approximately 5 minutes, while at the same time reducing the boil-off losses occurring during filling to less than 8% of the liquid volume transferred. Successive vehicle tank filling can be achieved within 3 minutes. This was mainly accomplished by using a new design of clean-break coupling systems for connection between the filling station and vehicle fuel tank. Beyond that, SWB ordered a 125 liter vehicle tank system without cryovalves, which was used during the second half of 1996 to achieve filling in about 3 min while eliminating return gas flow. Work on the task of automating operation of the Phase 1 LH_2 filling station has been completed. The filling station and the novel vehicle tank system remain on site for coupling demonstrations using the coaxial coupling system. At the same time, wearing behavior of components subject to stress remains under observation.

Picture 1.7: Test vehicle's liquid hydrogen filling station

6. SAFETY CONCEPT

6.1 Operation with limited attendance

As a rule, the solar hydrogen facility at Neunburg vorm Wald is manned by operating staff on workdays only, for one eight-hour shift from November-February, and two eight-hour shifts during the remainder of the year. When required for special test programs, the plant may be operated around the clock. As was to be expected, repeated starting and stopping of the plant has proved to slow down the test programs. On top of that, it causes heavier wear on the plant components. Under an arrangement with the licensing authorities, the gas production and utilization systems are shut down during the time the plant is unmanned.

A catalogue of measures was ultimately defined in cooperation with the licensing authorities as a prerequisite to temporary unsupervised operation of hydrogen systems (restricted to periods of 24 h). This involved adapting or utilizing the existing control systems for safety engineering duties, such as redundant monitoring of H_2/O_2 gas purities downstream of the alkaline low-pressure electrolysis and installation of pressure switches ahead of all mechanical safety valves in the H_2/O_2 gas route. Starting in September 1997, overnight unmanned running of some plant subsystems (alkaline low-pressure electrolyzer, H_2/O_2 gas systems, gas-fired heating boiler 2, catalytic heater, catalytically heated absorption-type refrigeration unit, and phosphoric acid fuel cell plant without oxygen-enriched air) became possible.

The permission to also operate the alkaline pressure-type electrolyzer according to this philosophy was granted by the licensing authority in August 1998, with operation expected to start in November 1998.

6.2 Basic elements of the safety concept

The operating concept described above is part of the safety-related requirements, as is of course observance of pertinent standard practice, occupational safety codes and explosion protection regulations for the chemical industry.

Experience gained by SWB shareholders from operating power stations, designing and operating chemical plants and cryogenic tank systems similarly entered into the planning of the safety measures, all of which were defined in collaboration with the licensing authorities.

The safety aspects for Neunburg vorm Wald reviewed here are those related to working with hydrogen. Structural and design provisions were made for the hazards associated with hydrogen during construction of the plant and buildings and were complemented by control and safety devices as well as operational measures. Other potentially hazardous fluids present in the plant (natural gas, oxygen, carbon monoxide, nitrogen, potassium hydroxide) are not considered in this report.

Generally, four types of safety measures may be defined:

Primary safety measures are directed at excluding sources of trouble, i.e., any formation of an ignitable mixture of hydrogen and air or oxygen. For that reason, the hydrogen was confined as safely as possible within the process equipment by appropriate engineering design and the use of approved materials of construction. Supporting measures include optimization of construction and layout, efficient ventilation systems, gas alarm systems and inertization of equipment with nitrogen.

Secondary safety measures concern the elimination of all possible ignition sources. Electrically or mechanically generated sparks are important ignition sources to be taken into account. Examples of the measures adopted are adherence to defined explosion proofing classifications and rules for maintaining safe distances around equipment and maintaining ground potential by connecting all electrically conducting equipment to a grounding system. It is obvious that smoking and open flames are prohibited throughout the fire and explosion hazard zones of the facility.

Tertiary safety measures have the purpose of minimizing the extent of damage in the event that both the primary and secondary measures should fail. At Neunburg vorm Wald these took the form of appropriate civil engineering and fire control procedures and action.

Additional precautions may be regarded as collective safety measures. Among these are the safety control system, uninterruptible power supplies for control systems and safety related electrical equipment, observance of safety notes contained in operating manuals and instructions, training courses and briefings, and routine inspection of equipment as directed by law or authorities.

It may be noted that no fundamentally new safety risks had to be considered when drafting and subsequently implementing the safety concept in force at the Neunburg vorm Wald solar hydrogen facility. It has been confirmed that, in industrial applications, the existing codes and regulations are adequate for safe working with hydrogen, a fluid that has been widely used in industry for decades both in gaseous and liquid form.

Long-term operating experience to date has given no cause to amend the concept for a still higher level of safety. Stipulations have been fulfilled that injury to persons present at the facility, damage to property and harm to the environment must be prevented.

The facility - largely constructed of prototype units as previously mentioned - has operated safely and without problems for about eight years now, not least of all thanks to the adequate safety engineering provided and the experience of the operating personnel. Except for a local cable fire in March 1991, which was put down by the operating crew with hand-held extinguishers, there have been no critical incidents.

Cooperation with the licensing authorities involved has proceeded on a decidedly positive note.

7. FUTURE POTENTIAL AND FUTURE PLANS

Assessing the work to which SWB has contributed, it is apparent that the beginnings of energy supply based on hydrogen as an energy medium are tied to prior expansion of electric power generation from renewable resources on a substantial scale. Storage of energy will only become meaningful when the electric power thus generated, concomitant with a shift away from fossil fuels, cannot be fully consumed as it is generated. Hydrogen and electric power are not competing alternatives.

One exception at the present time may be road transport, which will become reliant on a clean, readily storable motor fuel for control of source emissions in densely populated areas. Efforts are additionally being undertaken to make small-capacity cogeneration plants based on commercial phosphoric acid and molten carbonate fuel cell plants competitive with gas engines to exploit their better electrical and overall efficiency. Membrane and solid oxide fuel cell plants are also being investigated at the present time for small-capacity stationary applications. Realistic potentials for reducing the cost of individual plant subsystems should be explored further so as to successively narrow the gap to competing systems.

Even when regarded apart from the photovoltaic systems utilized at the site for electric power generation free of CO_2, the work undertaken in the field of hydrogen at Neunburg vorm Wald - this constituting the main focus of the project - furnishes valuable know-how for future hydrogen scenarios. It has, moreover, been shown that the process engineering and electrochemical attributes of these hydrogen systems make them more closely related to conventional plant engineering and construction than would appear to be conveyed by the term "solar technology", under which hydrogen is frequently classified in its capacity as an energy medium.

At the present time, any decision favoring long-term energy storage system based on hydrogen is still remote. Over time, however, the prospects for hydrogen could grow increasingly better. The appropriateness of a balanced energy mix will hold true for the future as well.

Over the past ten years of running the Neunburg vorm Wald demonstration project, SWB has acquired a wide range of know-how that is already utilized in accordance with the progress of experience. This covers conceptual design and possible realization of new (solar) hydrogen projects. Included among these are:

- WIBA, Co-ordination of Bavarian Hydrogen Initiative
- Munich Airport Hydrogen Project (preparatory project)
- Fuel Cell Propulsion for Municipal Buses and Trucks
- Munich New Exhibition Centre 1 MW Photovoltaic System (world's largest rooftop system).

The variety of experience gathered from the Neunburg vorm Wald project speaks strongly for the advisability, or rather need, to supplement basic research and development work by continuing technology-oriented demonstration and experimental projects on an industrial scale for practical test operation of prototypes.

Such use of hydrogen as an energy medium, with growing emphasis on economical viability of hydrogen utilization under operational conditions, will lend further support to its market introduction.

8. CONCLUSIONS

One aspect revealed in the course of running the SWB project in Neunburg vorm Wald is that hydrogen systems for energy conversion are for the most part only to be purchased at the present time as prototypes or individually engineered designs. In addition, their integration into a meaningful overall plant concept is often more difficult than commonly believed. For instance, the extent and complexity of the associate peripheral systems is often underestimated. The multitude of necessary utility and auxiliary systems required underscores the fact that large capacity hydrogen facilities are plant engineering and construction projects subject to individual planning.

Closely centralized generation and storage of the gas and its subsequent utilization as an energy medium is mandatory not only in the interests of cost reduction but also with a view to optimum attendance, service and safety installations. Beyond that, it is desirable that major plant subsystems for gas generation and utilization be constructed as outdoor installations, unlike the indoor configuration selected for the Neunburg vorm Wald facility. The decision there (based, in part, on the supplier’s conditions) to install the majority of prototypes in a common operating building for convenience of attendance and servicing, as well as for security considerations, necessitates extensive peripheral systems that would not otherwise be required. Frequently, the overall plant had to be shut down and the entire operating building inertized when work was required on individual systems. Since there is almost always work going on at some point in a test facility of this nature, and given the purposely planned complexity described above, the operating hours logged by some systems have been rather modest.

On the whole it can be stated that several of the systems installed at the solar hydrogen facility failed to work satisfactorily at the start. Throughout the operating period to date, SWB has, however, been able to adequately solve almost all of the problems occurring, and some recurring, both on individual subsystems and in interaction of the systems. In the course of so doing, several improvements have been devised, usually in collaboration with the system suppliers. Contributions to the inception of several new developments have likewise come out of the project. Examples of this, included in Figure 2, are certain solar cell technologies (e.g., AS hybrid, HE and BSF), the alkaline low-pressure electrolyzer, the two gas-fired heating boilers, the catalytic heater and absorption-type refrigeration unit with catalytically heated desorber, use of an alkaline pressure-type electrolyzer, the air-oxidizer membrane fuel cell plant, as well as the two advanced coupling systems and vehicle tank system without cryovalves for liquid hydrogen fueling of test vehicles. Stimulation of these developments is an important outcome of the project and wholly in keeping with SWB's objectives.